EVALUATION OF RADIOACTIVE SAND TRACERS TO MEASURE LONGSHORE SEDIMENT TRANSPORT RATES

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ABSTRACT

This paper analyzes and compares radioactive sand tracer experiments with beach profile measurements and calculations of littoral sand transport rates performed at Pointe Sapin, N.B. in the Gulf of St. Lawrence, Canada. The three methods give comparable results. In theory, all sediment tracers should be dealt with the same way, but in practice the nature of the tracers has to be taken into account. Tracers do fulfill the purpose for which they are used and they can solve sediment transport problems when used with knowledge and care. The wide variation among littoral sediment transport formulas should not be attributed to the lack of accuracy of tracer experiments but rather to the fact that expressions are over-simplistic and important factors such as the influence of beach slope and grain size are not taken into account.

1. INTRODUCTION

The determination of alongshore sediment transport rate remains one of the fundamental problems of coastal engineering. The Canadian Coastal Sediment Study (C^2S^2) brought together oceanographic, geological, and engineering researchers in Canada to study coastal processes and improve the knowledge of sand transport on beaches (Willis, 1987). One of the main achievements of (C^2S^2) has been to coordinate different experiments at two sites in the Gulf of St. Lawrence: Pointe Sapin, N.B. and Stanhope Lane, P.E.I. The purpose of this paper is on the one hand to analyze and compare radioactive sand tracer experiments with beach profile measurements and calculations of littoral sand transport rates performed at Pointe Sapin and on the

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other hand to compare these results with sand tracer experiments carried out elsewhere.

As the sediment tracer measurements are compared with other measurements and calculations of sediment transport carried out simultaneously at the same site, it permits verification of the capabilities as well as the limitations of the sediment tracer technology. Sediment tracer results have been one of the main sources of information to develop littoral transport formulas. The behavior of tracer particles in the longshore sediment transport system has been examined by Madsen (1987) who points out that sediment tracer experiments must meet many assumptions to sustain the theory on which the sediment tracer technology is based and he concludes that in his opinion whether or not the longshore sediment transport system invalidates the assumptions behind the use of tracer methodologies is not yet resolved.

In this study the spatial integration of radioactive tracers is used to determine sediment transport rates. The basic assumption behind the use of tracers is that advection, the downstream transport of sediments associated with the flow in the transport system, dominates diffusion and dispersion. The use of tracers to measure longshore transport of sand in the surf zone is based on the principle of continuity described by a continuity equation such as:

$$Q = V_a b \tag{1}$$

where V_a is the mass velocity of the tracer and b is the thickness of the mobile sediment layer.

Inherent to the use of tracers is the problem of defining to what extent the observed movement of tracer grains is representative of the movement of sediment within which the tracer grains have been injected. There are two premises: one is that the trajectory of tracer grains is the same as that of the sediment in which they are injected, and the other is that the depth of mixing of the tracer is representative of the thickness of the mobile sediment layer.

The centroid of all tracer grains detected during a given survey is used to determine the mass velocity (V_a) of the tracer which is obtained by dividing the distance the centroid of the tracer cloud has moved between two surveys by the time elapsed between these two surveys. Tracers with the same grain size and density as the parent sediment are assumed to follow similar paths. The depth of mixing of tracer grains is more difficult to assess because sediment tracers are usually deposited at the water-sediment interface and their mixing within the sediment mobile layer is not instantaneous. The thickness of the moving sediment layer was estimated using an analytical solution developed by Sauzay (1967). Cores of the beach were also taken during the tracer experiment. The distribution of tracer within the cores shows different patterns depending on location and time, but a parabolic distribution is found in many cases that confirms Alquier's experimental verification (Alquier et al. 1970) of Sauzay's model as well as the theoretical tracer distribution, based on "waiting time considerations", developed by Galvin (1987).

In theory, all sediment tracers should be dealt with the same way, but in practice the nature of the tracers has to be taken into account. The time scale and the space scale of luminescent tracers and radioactive tracers differ by one order of magnitude. Luminescent tracer experiments are measured in terms of hours and tens of meters, while radioactive tracer experiments last many days and cover hundred of meters. These large differences imply that the results are interpreted differently.

2. EXPERIMENTAL SETTING

2.1 Location of study area

Two sites were selected in the Gulf of St. Lawrence for the Canadian Coastal Sediment Study; one was located at Pointe Sapin, N.B. and was occupied during the fall of 1983 and the other was located at Stanhope, P.E.I. and occupied during the fall of 1984. The present paper is dealing with the Pointe Sapin experiment (Fig. 1).

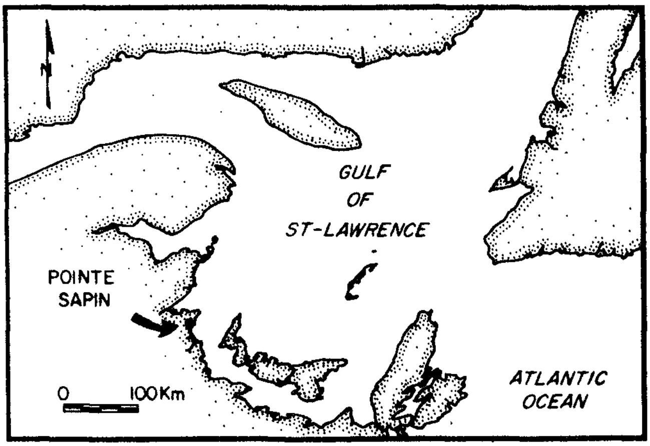

Figure 1. Location of study area.

Pointe Sapin is a small fishing harbor on the coast of New Brunswick in the Gulf of St. Lawrence. The location of this site is such that it is exposed to long fetches exclusively from the north-east. The Pointe Sapin site is then subjected to an almost unidirectional alongshore sediment transport, which is an advantage for studying the transport of sediments. Furthermore, the littoral sediment drift is terminating in a sand trap, a detached breakwater designed to keep Pointe Sapin Harbor entrance open (Fig. 2-A).

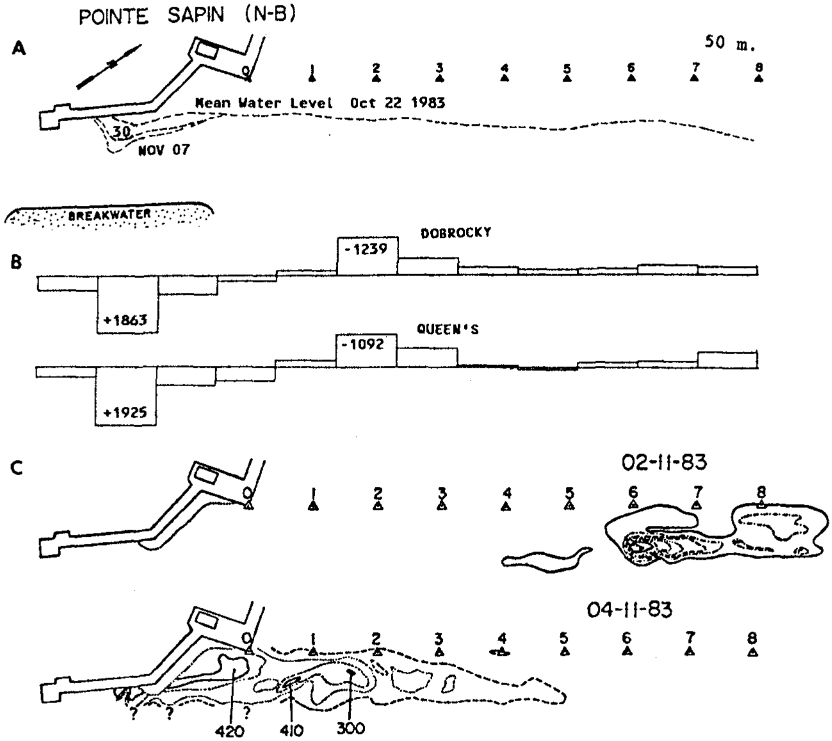

Figure 2. A) General setting. B) Measured (Dobrocky) and calculated (Queen's) transport rates. C)Sediment tracer distribution before and after Nov 4 storm.

2.2 Field measurement program

The Canadian Coastal Sediment Study measured: 1) directional waves at 4 km and 750 m. offshore 2) currents at 1100 m. and 700 m. offshore and in the surf zone, 3) beach profiles, 4) volumetric sand transport at the trap, 5) suspended sediment concentration, and 6) dispersion of radioactive tagged sand.

2.3 Sand trap at Pointe Sapin

The study site at Pointe-Sapin benefits from a detached breakwater that serves as a sediment trap filling up on a yearly basis. Figure 2-A shows the evolution of the sand trap that had been dredged in September 1983, prior to the field operations, and then partially filled during the field study, mostly during the passage of two north-easterly storms over the area (October 25th and November 4th, 1983).

2.4 November 4th storm

Two north-easterly storms developed during the field experiment; one on October 25th and the other on November 4th. The results from the present study are centered on November 4th storm. Periods of dominant waves varied from about 3 seconds during calmer conditions, up to nearly 10 seconds for the two storm events. Immediately prior to the Nov. 4th storm, the wave period gradually increased, as typical of a developing local storm system. Because of the geometry of the coastline and the adjacent islands, the wave field did not shift in direction significantly as the storm front passed. This is largely due to the narrow window through which waves may pass to impinge onto Pointe Sapin. During the November 4th storm, significant wave height exceeded 1.25 m, propagating towards 272-273 degrees TN with periods of 8.5 seconds, growing to 9.8 seconds near the end of the storm (Aubrey and Spencer, 1984).

3. RESULTS

3.1 Volume measurements of erosion and sedimentation

Beach and bathymetric profiles of the sand trap and the adjacent beach and nearshore zone were measured regularly and also after each storm by the Dobrocky-Seatech group (Gillie, 1984). Consecutive sets of profiles were compared to determine the volumes of erosion and sedimentation. A complete survey was carried out before (Oct. 30th) and after (Nov. 7th) the November 4th storm. The erosion and sedimentation of the beach and sand trap resulting from that storm are shown in Fig. 2-B.

3.2 Tracer measurements

The radioactive element used for the sediment tracer study was gold^{198} (2.7-day half-life) incorporated in glass grounded to the size of the beach sediment. One kilogram of sediment tracer was injected on November 1st at the location of marker #6 as shown in Fig. 2-C (Long, 1984). Twelve surveys of the radioactive tracer were carried out during the nine following days (Table 1). The distribution of tracers before (03 Nov. 15:00 hrs) and at the end of the storm (04 Nov. 15:00 hrs) is shown in Fig. 2-C.

Table 1

Tracer Experiment Paramèters

Time (hrs)	Q (m^3/hr)	b (cm)	X (m)	Y (m)
12.00	0.00	0.00	500.00	33.000
34.00	-0.06	2.10	502.07	33.250
40.00	-0.88	7.00	504.01	34.250
59.00	-0.98	11.80	508.10	32.650
63.00	-2.66	9.30	511.74	37.050
84.00	271.53	50.80	244.49	25.000
87.00	143.67	55.60	218.65	21.920
107.00	23.00	48.10	226.72	35.000
132.00	31.41	45.20	151.00	31.900
156.00	-7.77	23.80	170.56	32.920
179.00	1.50	9.50	243.92	32.720
208.00	-0.05	5.30	166.97	34.150

Time = time in hours starting at 00:00 hrs 01/11/83
Q = sediment transport rate
b = depth of mixing of tracer
X = longshore coordinate of tracer cloud centroid
Y = crossshore coordinate of tracer cloud centroid

3.3 Calculations of erosion and sedimentation

Kamphuis et al. (1986) developed a model based on the wave energy flux to calculate littoral sand transport rates. This model was used at Pointe Sapin to calculate sand transport rates as well as erosion and sedimentation in the study area for the November 4th storm (Kooistra and Kamphuis, 1984) . The results are shown in Fig. 2-B and in Fig. 3.

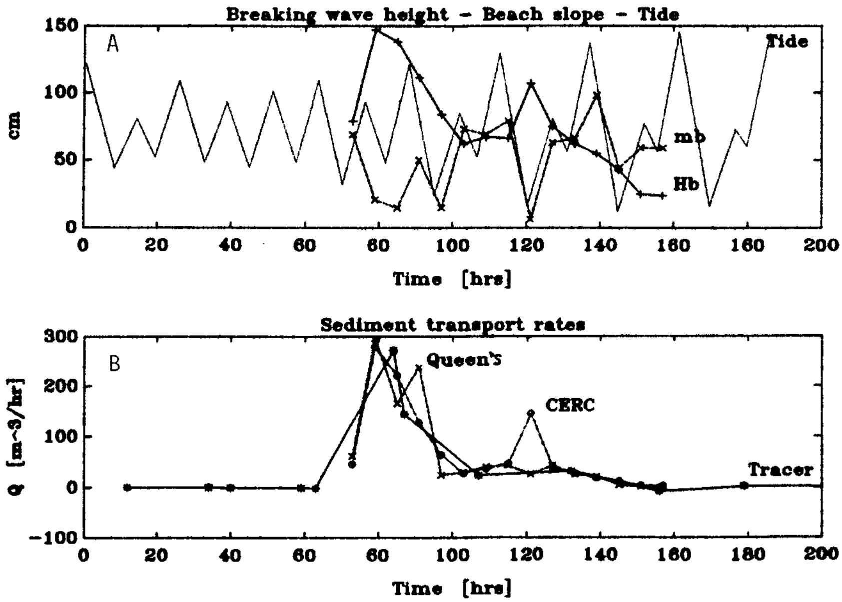

Figure 3. Time series starting at 00:00 hrs Nov. 1st 1983.
A) Tide height (Tide [cm]), Beach slope (mb [x1000])
Breaking wave height (Hb [cm]).
B) sediment transport rates.

4. DISCUSSION AND CONCLUSIONS

4.1 Coherence of Pointe Sapin results

Estimates of total volume of sediments transported during the November 4th storm are shown in Tab. 2.

Table 2

Transport using volume method		5200 m^3
Transport using tracer method		
	30 m. wide beach	5300 m^3
	40 m. wide beach	7100 m^3
Calculated transport:		6070 m^3

These results outline the good agreement between the three methods used at Pointe Sapin. As explained above, the Pointe Sapin site is particularly appropriate to perform comparative studies because uniform conditions are maintained during storm events. Time series of littoral drift estimates based on: a) 12-hourly tracer surveys, b) 6-hourly calculations based on Queen's model (Kooistra and Kamphuis, 1984), c) 12-hourly calculations based on CERC formula are compared in Fig. 3-B, using wave height, tide and beach slope of Fig. 3-A. These time series show that the tracer method estimates concur with the littoral drift calculations. It is worth noticing that although the tracer method calculations for littoral drift are based on a spatial integration, they are nonetheless sensitive to short-time variations of the wave climate. Fig. 3-B also shows that the CERC formula is directly linked to the wave climate exclusively, while the Queen's formula also incorporates the beach slope. This is the reason why at hour 120 in Fig.3-B the CERC formula shows a peak which is reflected neither by the Queen's estimate nor by the tracer measurements.

4.2 Comparison with other studies

Extensive field experiments on longshore sand transport in the surf zone have been carried out in Japan. The results of these experiments were synthesized by Kraus et al. (1982). Eight sand tracer experiments were performed in energetic surf zones on natural beaches and on beaches near structures to measure short-term longshore sand transport rates. Tracers of up to four distinct colors were used to better outline the distributions of the longshore sand advection velocity and transport rate.

The transport rate of sediments is related to the fluid energy dissipation on the shore. Kraus et al. (1982) obtain the relationship:

$$Q = 0.024 H_b^2 V \qquad (2)$$

where Q is the volumetric transport rate, H_b the wave height at breaking and V the average longshore current, assuming a beach slope of 1/50 and a breaking index of 0.8. This equation is plotted in Fig. 4 as well as the results from the Japanese tracer program. It can be seen that the equation is a good descriptor of the Japanese tracer data from which it is derived. Tracer results from Pointe Sapin are shown on the same figure. The energy dissipation levels are comparable for the two sets of data but the corresponding transport rates are one order of magnitude larger in the case of Pointe Sapin.

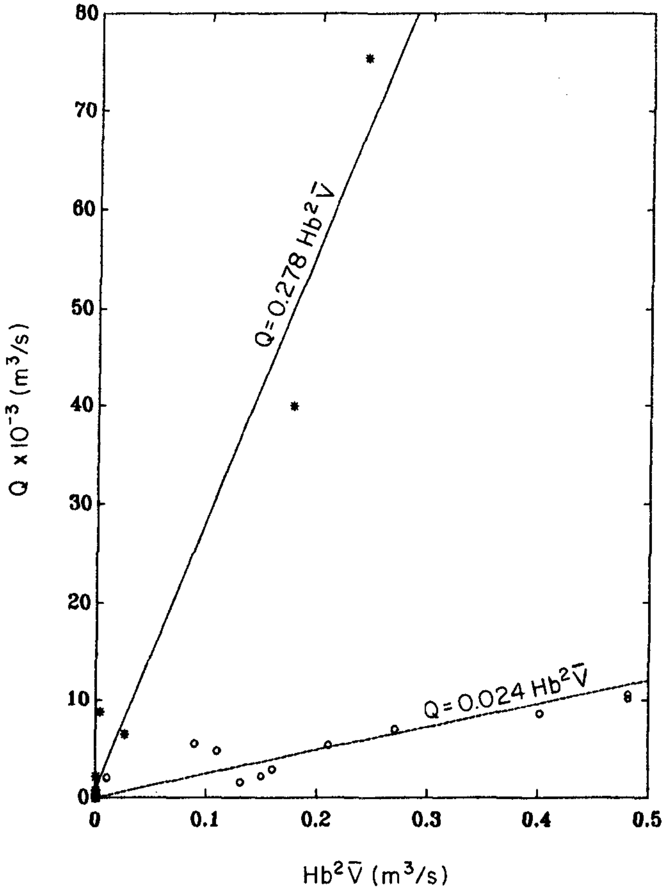

Figure 4. Volumetric transport rate.
O = Kraus et al. 1982 data.
* = This study.

Kraus et al. (1982) arrive at that definition of equation 2 using two other equations derived empirically from their field measurements:

$$V_a = 0.014V \qquad (3)$$

$$b = 0.027H_b \qquad (4)$$

where V_a is the tracer cloud centroid advection velocity, b the depth of tracer mixing and the other parameters are the same as Eq. 2.

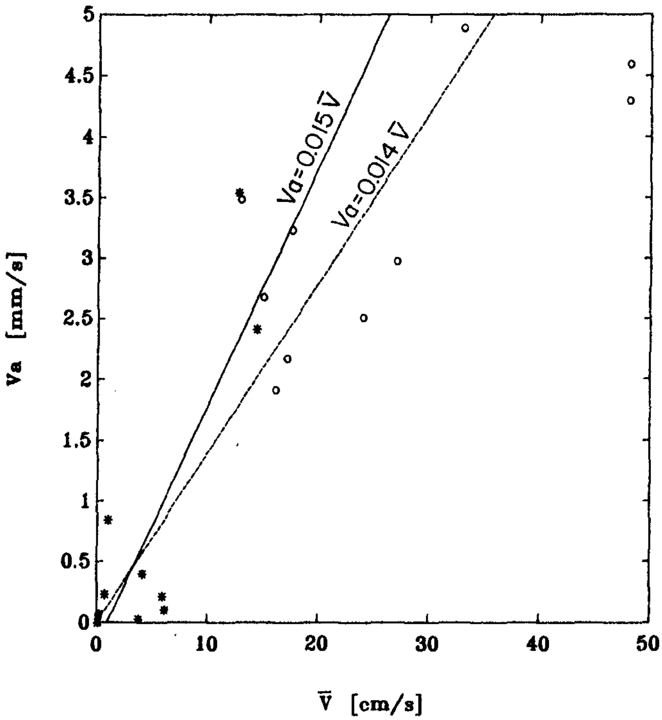

Figure 5. Sand advection velocity.
O = Kraus et al. 1982 data.
* = This study.

Equation 3 establishes a relationship between the mean longshore current (V) and the sand advection velocity (V_a). The results from the Japanese program and those from Pointe Sapin are plotted on the same diagram in Fig. 5. In this case the results from Pointe Sapin and those from Kraus et al. (1982) concur, which implies that for comparable conditions the advection of sand in the longshore transport process is essentially the same be it on Japan beaches or in the Gulf of St. Lawrence.

Equation 4 which correlates the depth of tracer mixing to the wave height is plotted in Fig. 6. Here again the results from Pointe Sapin are one order of magnitude larger than those from Japan beaches. It indicates that transport rates obtained for the present study are different from those obtained by Kraus et al. (1982) for comparable energy conditions because estimates of thicknesses of the mobile sediment traction layer are different.

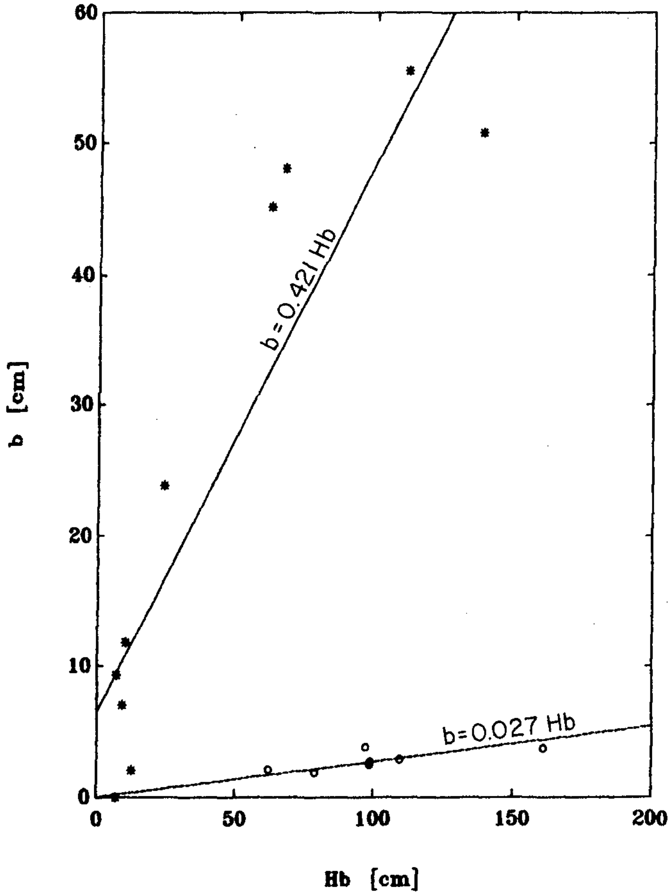

Figure 6. Depth of mixing.
O = Kraus et al. 1982 data.
* = This study.

The thickness of the mobile layer is determined indirectly when radioactive tracers are used. It is based on the evaluation of the diminution of tracer signal as a function of depth of burial into the sediment (Sauzay, 1967). With luminescent tracers the thickness of the mobile layer is determined by coring the sediment and sampling at different intervals. Kraus (1985) has examined the vertical mixing of luminescent tracer within the sand of the surf zone for the eight

Japanese experiments referred above. He takes the thickness of the mobile layer to be the depth where 80 percent of the total tracer included in the core is reached. The results of Kraus et al. (1982) plotted in Fig. 4, 5 and 6 are based on that premise.

Galvin (1987) has reviewed the problem of vertical distribution of sand tracers in the littoral zone. He approached the problem using a stratigraphic as well as a hydraulic analogy and developed the concept of waiting time. This concept explains, from theoretical considerations, how a given quantity of tracer grains evolves as a function of time as well as a function of distance from the tracer source . These results show that the depth of mixing and also the distribution of tracer change as time passes after the initial tracer release. This is particularly relevant when radioactive tracer experiments are compared with luminescent tracer experiments. Luminescent tracer experiments last less than a day and cover a few tens of meters. By contrast radioactive tracer experiments last for many days and cover hundred of square meters.

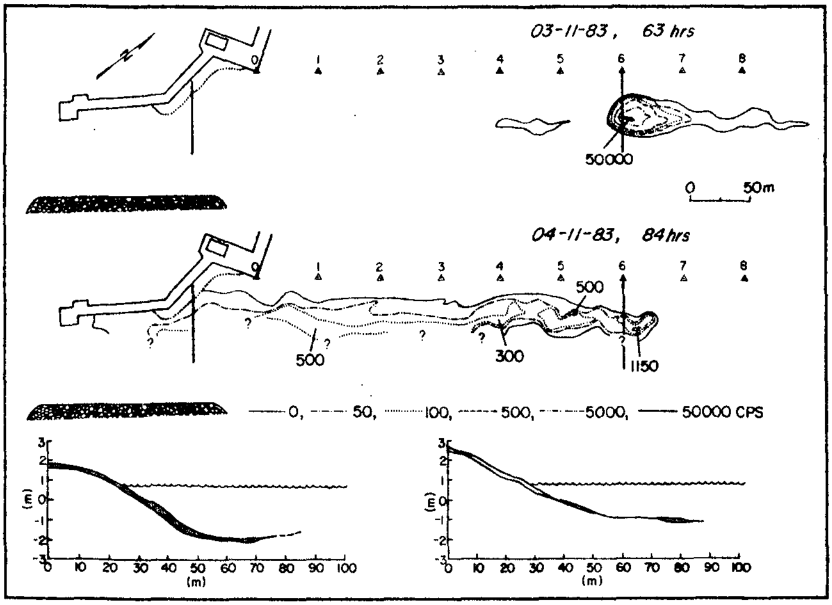

Figure 7. Distribution of tracer cloud before the November 4th storm (03/11/83 63 hrs) and after the storm (04/11/83 84 hrs) Beach profiles surveyed on Oct. 30 and Nov. 7, at station #6 and at the wharf, are shown on the lower portion of the figure. Sedimentation is identified by gray tone.

It is not surprising then that the estimates for the depths of mixing are not the same. If one refers to Galvin's (1987) Fig. 5, it can be seen that if radioactive and luminescent tracer experiments were performed at the same site they would produce different results, the radioactive tracer experiment yielding deeper mixing depths because it lasts longer and covers a larger area.

Data from Tab. 1 show that the depth of mixing during the first 40 hours of the Pointe Sapin experiment is comparable with what was measured on Japanese beaches. The values obtained for the depth of tracer mixing at Pointe Sapin are verified by comparing depth estimates of tracer mixing with beach profile measurements. Beach profiles across the tracer clouds are shown in Fig. 7. Profiles surveyed before and after the Nov. 4th storm are drawn on that figure. Erosion is dominant along profile #6 while sedimentation is prevails along the beach profile extending between the wharf and the detached breakwater. The thicknesses of erosion and sedimentation obtained by comparing beach profiles are in agreement with the depths of mixing estimates shown in Tab. 1.

Conclusions that can be drawn from this study are: 1) tracers do fulfill the purpose for which they are used and they can solve sediment transport problems when used with knowledge and care; 2) the wide variation among littoral sediment transport formulas should not be attributed to the lack of accuracy of tracer experiments but rather to the fact that expressions are over-simplistic and important factors such as the influence of beach slope and grain size are not taken into account.

5. ACKNOWLEDGMENTS

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